Current status and future development of the NCEP GFS deep and shallow cumulus convection schemes

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GFS PBL scheme

- Before January 2015 implementation, a K-profile method with a counter-gradient mixing term (γ_h) is used, so called as eddy-diffusivity counter-gradient (EDCG) PBL scheme (Troen & Mahrt, 1986; Hong & Pan, 1996)

$$\overline{w'\theta'} = -K_h^{surf}\left(\frac{\partial\theta}{\partial z} - \gamma_h\right) \qquad K_h^{surf} = \mathrm{Pr}^{-1}\kappa w_s z\left(1-\frac{z}{h}\right)^2$$

- In July 2010 upgrade, the PBL scheme is revised to enhance turbulence mixing in stratocumulus regions (Han & Pan, 2011)

$$\overline{w'\theta'} = -\left(K_h^{surf} + K_h^{Sc}\right)\frac{\partial\overline{\theta}}{\partial z} + K_h^{surf}\gamma_h \qquad K_h^{Sc} = 0.85\kappa V_{Sc}\frac{(z-z_b)^2}{h_b - z_b}\left(1-\frac{z-z_b}{h_b-z_b}\right)^{1/2}$$

- In January 2015 upgrade, an eddy-diffusivity mass-flux (EDMF) PBL scheme is implemented for the strongly unstable PBL. And the heating by turbulent kinetic energy (TKE) dissipation (ε) is also parameterized (Han et al., 2015?)

$$\overline{w'\phi'} = -K\frac{\partial\overline{\phi}}{\partial z} + M(\phi_u - \overline{\phi})$$

$$c_p\left.\frac{\partial\overline{T}}{\partial t}\right|_{diss} \approx \varepsilon$$

$$\varepsilon \approx \frac{g}{\overline{\theta}_v}\overline{w'\theta_v'} - \overline{u'w'}\frac{\partial\overline{u}}{\partial z}$$

BMJ (Betts-Miller-Janjic) cumulus convection scheme
(Courtesy from Zavisa Janjic)

- Used in NCEP regional models.
- Moist convective adjustment scheme.
- Adjust toward a reference temperature profile, of which the final profile is obtained in an iterative procedure together with the moisture profile (Betts,1986; Betts & Miller, 1986; Janjic, 1994).
- Use regime dependent moisture profiles and relaxation time (Janjic, 1994).
- Use a "minimum microphysics" where the grid precipitation starts as soon as saturation is reached and the condensate evaporates in lower unsaturated layers as long as any of it is left, so that the process stays on a moist adiabat.
- Unlike a mass-flux scheme, there is basically no convergence issue with increasing resolution although adjustments of tunable parameters are needed with different resolutions.

RAS (Relaxed Arakawa-Schubert) convection scheme
(Courtesy from Shrinivas Moorthi)

- Optional cumulus convection scheme in NCEP global model using mass flux parameterization.
- Used in NGAC (NEMS GFS Aerosol Component).
- Invokes multiple clouds detraining at different model levels every time step and each clouds modify the environment by a fraction of the mass flux needed to fully stabilize s single cloud, thus relaxing the state towards equilibrium (Moorthi and Suarez, 1992, 1999).
- Simple ice phase for the cloud condensate included.
- Cheng and Arakawa (1997) downdraft is included (saturated or unsaturated).
- Downdraft can penetrate the boundary layer and influence surface evaporation.
- Downdrafts driven by precipitation loading and evaporation.
- Precipitation flux available for downdraft is obtained as a steady state solution to a tilted updraft.

RAS (Continued)

- Downdraft tilting angle is pre-assigned depending on cloud depth (~35 to 7.5 degrees).
- Precipitation is transported within the updraft; may be available for downdraft at different levels than where it was generated.
- Downdrafts can start anywhere and end anywhere in the domain.
- If downdraft solution does not exist, only updraft is used (downdraft is limited to deep clouds only P(top) < 500hPa).
- Momentum transport by convection is included.

GFS deep cumulus convection scheme
[Simplified Arakawa-Schubert (SAS) scheme; Pan & Wu, 1995]

- A bulk mass-flux scheme assuming that updraft fraction over a grid size is negligibly small.

$$\overline{w'\phi'} = M\left(\phi_u - \overline{\phi}\right)$$

- Based on a quasi-equilibrium closure of Arakawa and Shubert (AS; 1974), where the destabilization of an air column by the large-scale atmosphere is nearly balanced by the stabilization due to the cumulus.
- Consider a single plume ("Simplified") rather than cloud ensemble in AS.
- For the cloud model, an entraining and detraining plume model is used.

Major revision of the GFS deep cumulus convection scheme implemented in July 2010 (Han & Pan, 2011)

- To suppress excessive grid-scale precipitation (grid point storms) during the convective season, which often results from the convective parameterization not fully eliminating the instability and consequently causing explicit convective ascent to occur on the grid scale.
- Make convection stronger and deeper by such as having convective overshooting and by increasing maximum allowable cloud base mass flux.
- Trigger condition was also modified to produce more convection in large-scale ascent regions but less convection in large-scale subsidence regions.

Major revision of the GFS deep cumulus convection scheme implemented in July 2010 (cont.)

RH dependent entrainment rate (Betchtold et al., 2008)

$$\varepsilon = \varepsilon_0(z)F_0 + c_1(1 - RH)F_1$$

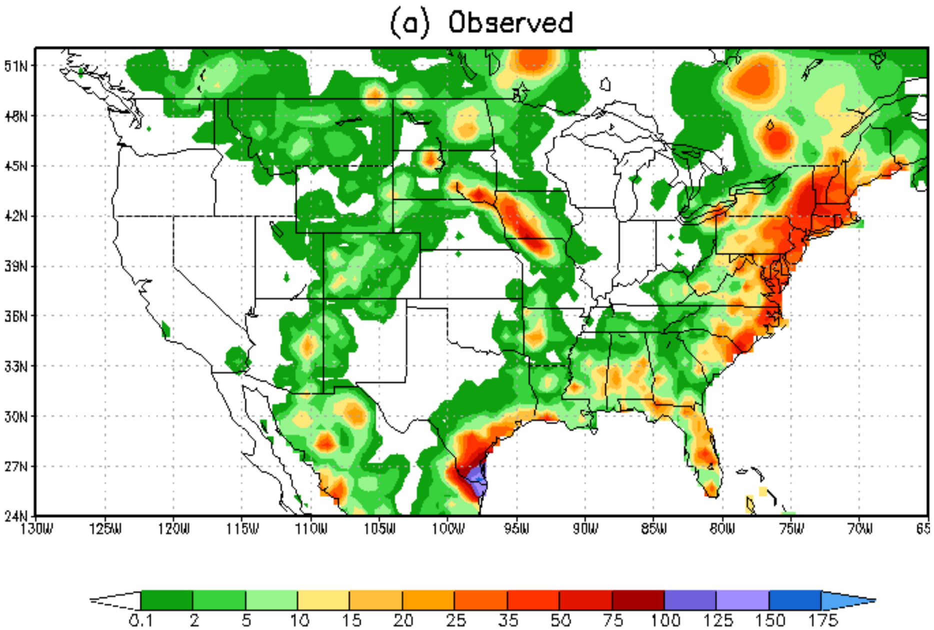
$$\varepsilon_0(z) = \frac{0.1}{z}$$ in sub-cloud layers

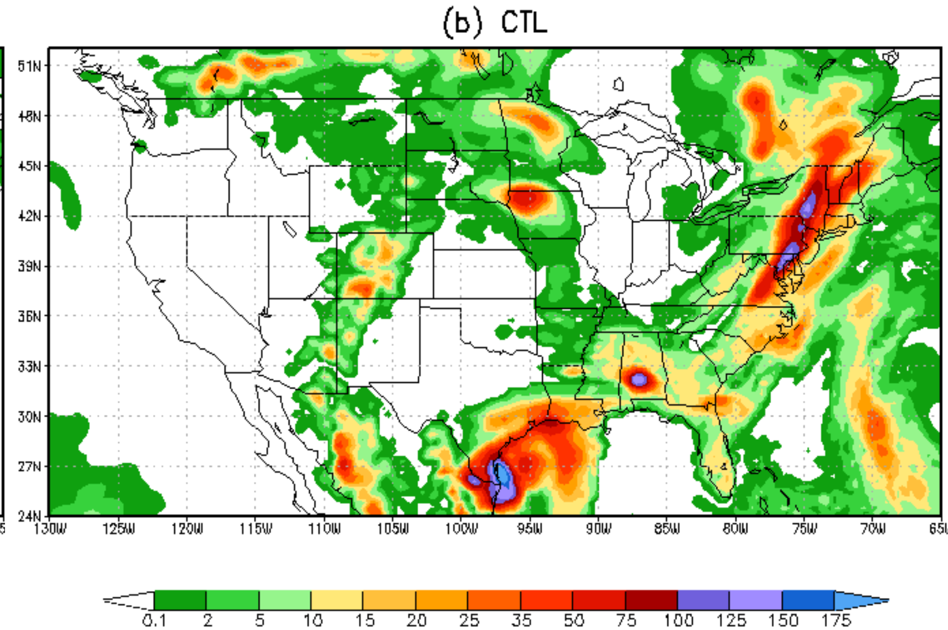
$$\varepsilon_0(z) = \varepsilon_0(z = z_b)$$ above cloud base

$$c_1 = 1.0 \times 10^{-4}$$

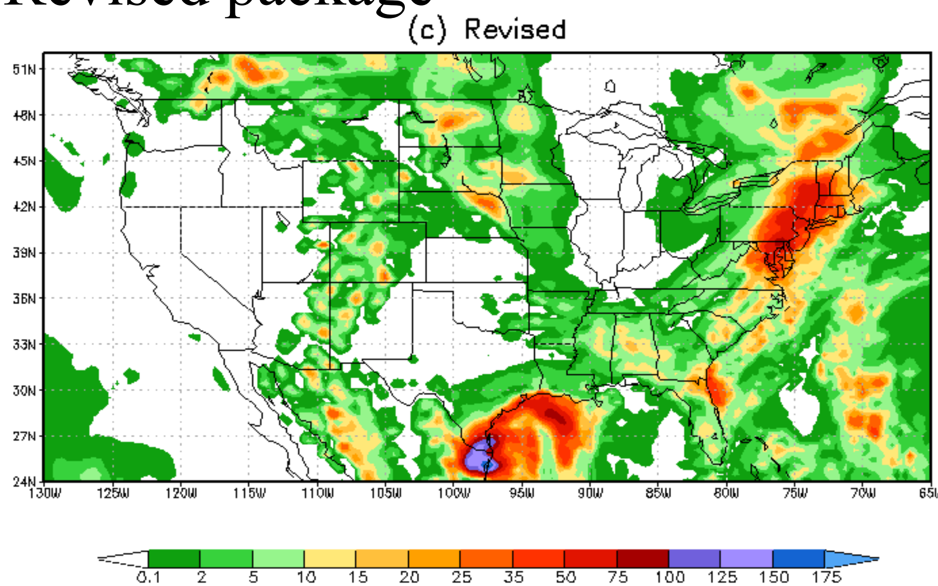
$$\delta = \varepsilon_0(z = z_b)$$

$$F_0 = \left(\frac{\bar{q}_s}{\bar{q}_{sb}}\right)^2, \quad F_1 = \left(\frac{\bar{q}_s}{\bar{q}_{sb}}\right)^3$$





Revised package

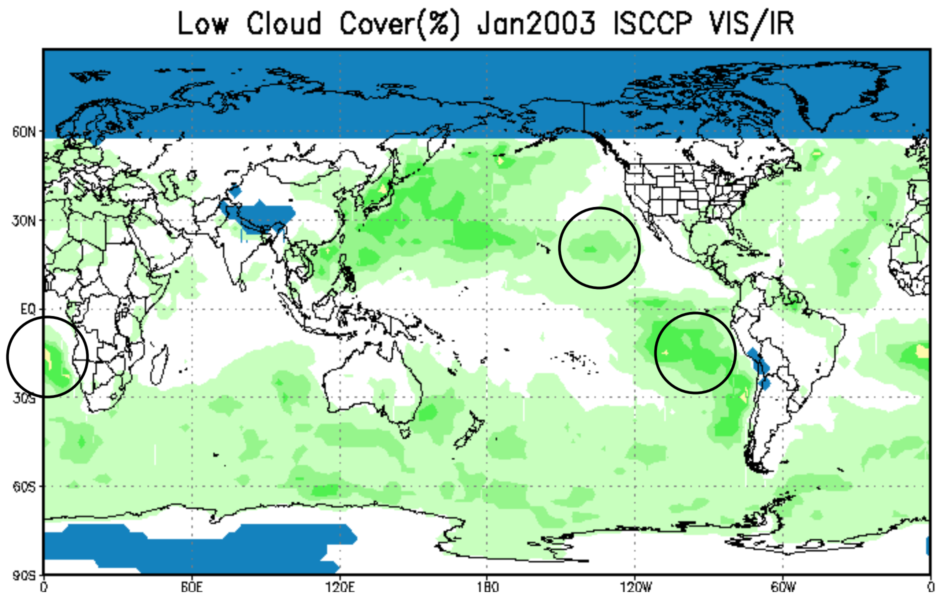


24 h accumulated precipitation ending at 12 UTC, July 24, 2008 from (a) observation and 12-36 h forecasts with (b) control GFS and (c) revised model

Major revision of the GFS shallow cumulus convection scheme implemented in July 2010

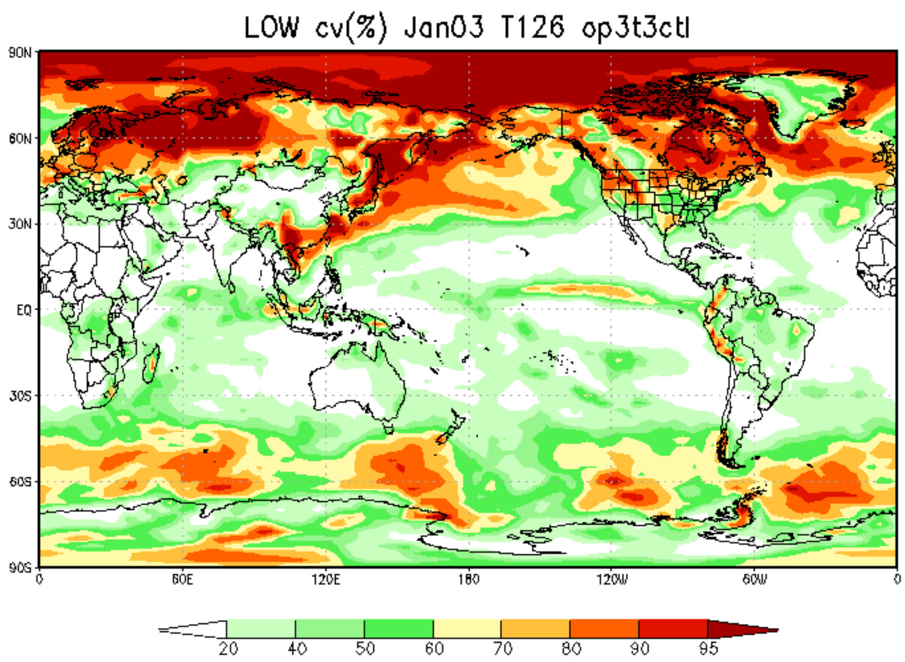
- Employs a bulk mass flux parameterization (same as deep convection scheme) replacing the old turbulent diffusion-based approach.
- Separation of deep and shallow convection is determined by cloud depth (currently 150 mb).
- Entrainment rate is given to be inversely proportional to height (which is based on the LES studies) and much larger than that in the deep convection scheme.
- Mass flux at cloud base is given as a function of the surface buoyancy flux (Grant, 2001). This differs from the deep convection scheme, which uses a quasi-equilibrium closure of AS.

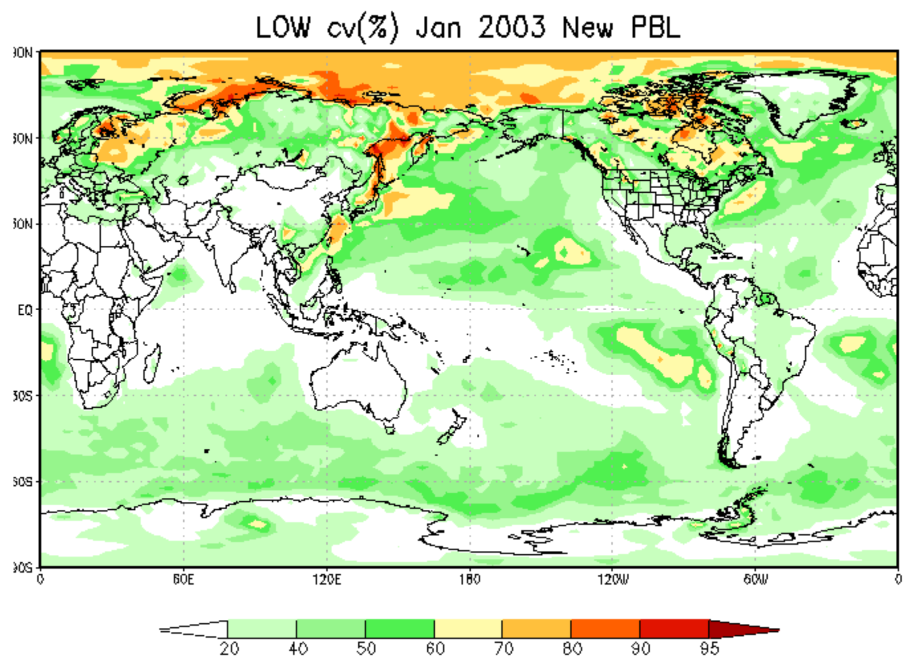
ISCCP



New Shallow with stratocumulus top driven diffusion

Old Shallow





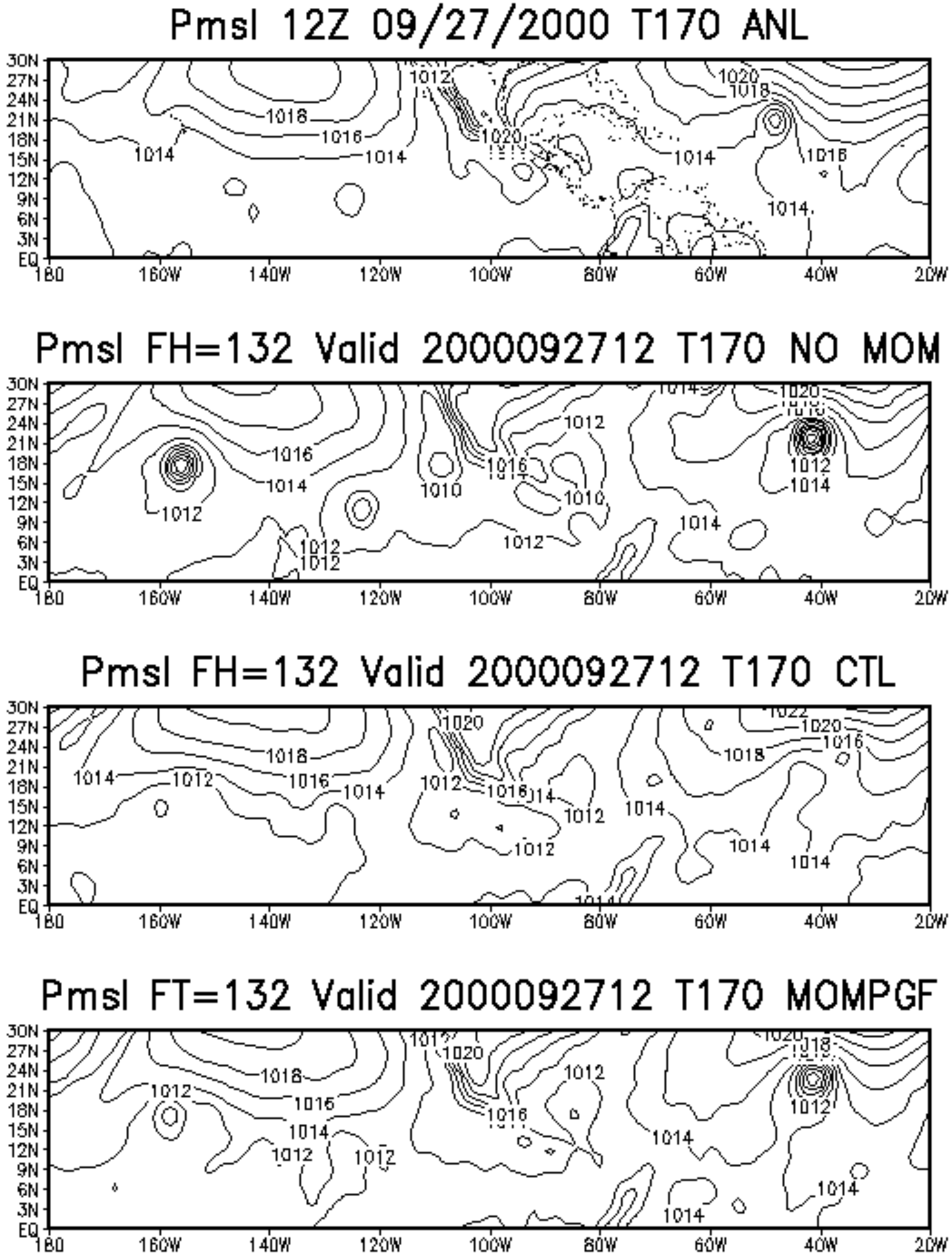
Reduction of convective momentum transport due to convection-induced pressure gradient force in both deep and shallow convection schemes

$$\frac{\partial \overline{V}}{\partial t} = (1-c) M_u \frac{1}{\rho} \frac{\partial \overline{V}}{\partial z} + \delta \left(V_u - \overline{V} \right)$$

c: effect of convection-induced pressure gradient force

c=0.0 in the old scheme

c=0.55 in the 2010 revision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30N 27N 24N 21N 18N 15N 12N 9N 6N 3N EQ
180 160W 140W 120W 100W 80W 60W 40W 20W

ALBERTO

Issues associated with the GFS cumulus convection schemes after 2010 revision

- The 2010 revision of deep and shallow cumulus convection schemes, which intends to suppress excessive grid-scale precipitation and to promote stratocumulus cloud formation off the west coasts of South America and Africa, gave significant improvements of forecast skills in such as 500 hPa height, continental US precipitation, and hurricane track. However,
- Too much convective precipitation even for higher resolution
- Too much light rains
- Unrealistically noisy (popcorn-like) rainfall especially over high terrains
- False alarm tropical storms especially in later forecast time (e.g., after forecast day 5)

Recent modifications for implementation in late this year

1) cloud base mass flux (m_b) calculation

Current:

$$m_b = \frac{A - f_{cr} A_{crit}}{\tau_{cnv}} \times \frac{m_b' \Delta t'}{A' - A}$$

A: cloud work function
(~CAPE [Convective Available Potential Energy])

$$\tau_{cnv} = \max\left[\min\left\{\Delta t + \max(1800 - \Delta t, 0) \times \left(\frac{\omega - \omega_2}{\omega_1 - \omega_2}\right), 3600\right\}, 1200\right]$$

Update:

$$A_{crit} = 0$$

Full CAPE elimination closure

$$\tau_{cnv} = a \frac{D}{w_u}$$

D: cloud depth
a=1.0

$$\frac{\partial w_u^2}{\partial z} = -b_1 \varepsilon w_u^2 + b_2 g \frac{T_v - \overline{T}_v}{\overline{T}_v}$$

2) Modification in rain/snow conversion rate

Current: $c_0 = 0.002 m^{-1}$ for both deep and shallow convections

Update: $c_0 = 0$ for shallow convection

$c_0 = 0.0015 \exp(0.07[T - T_0])$ $T \leq 0^0 C$

$c_0 = 0.0015$ $T > 0^0 C$

for deep convection (Lim & Hong, 2012)

It is derived based on cloud resolving model results for a convective storm.

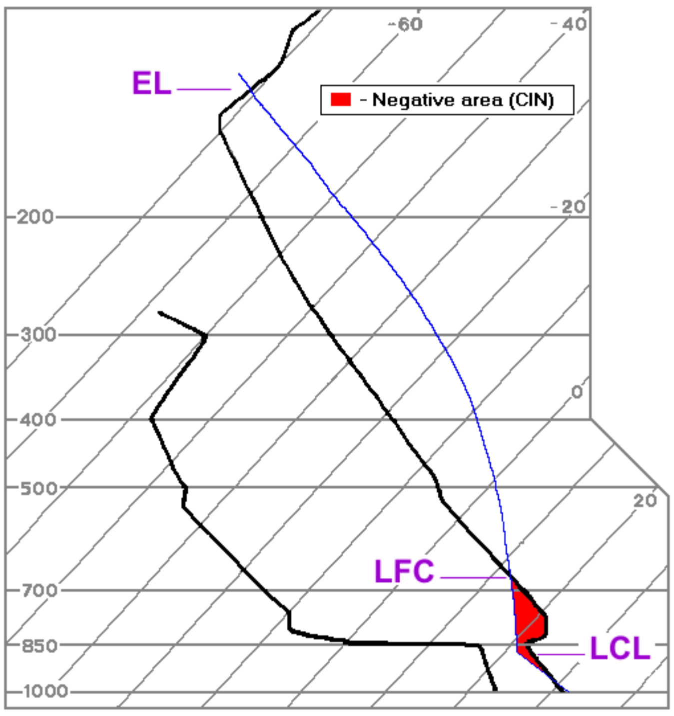
- Change in autoconversion rate coefficients in the microphysics scheme:

Ice to snow: 6.0×10^{-4} => 8.0×10^{-4}

Liquid water to rain: 1.0×10^{-4} => 2.0×10^{-4}

3) More constraint in trigger:

no trigger if CIN (convective inhibition) <-120(m^2/s^2)

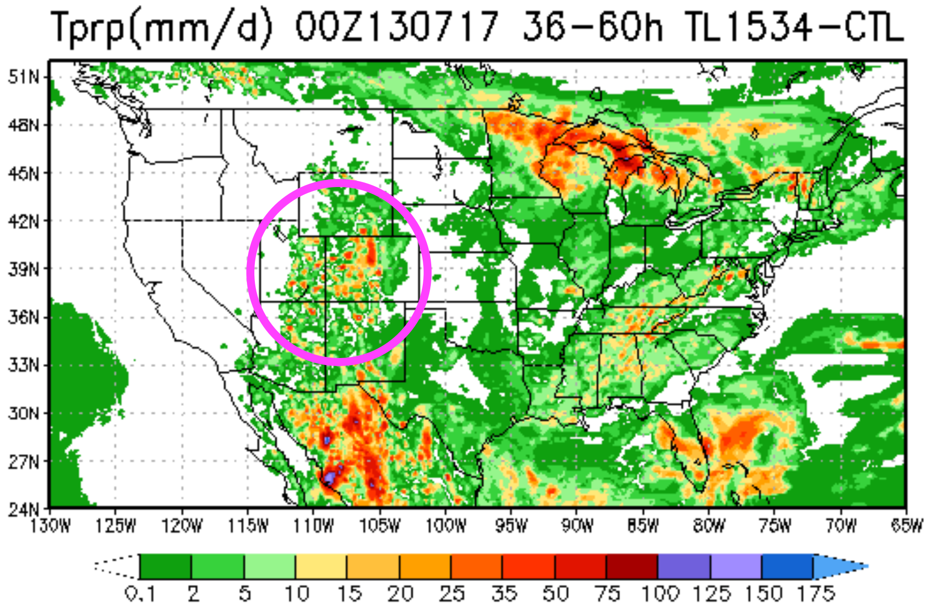


$$CIN = \int_{z_S}^{z_B} \frac{g}{c_p T(z)} \frac{1}{1+\beta} \left[h(z) - \bar{h}(z) \right] dz$$

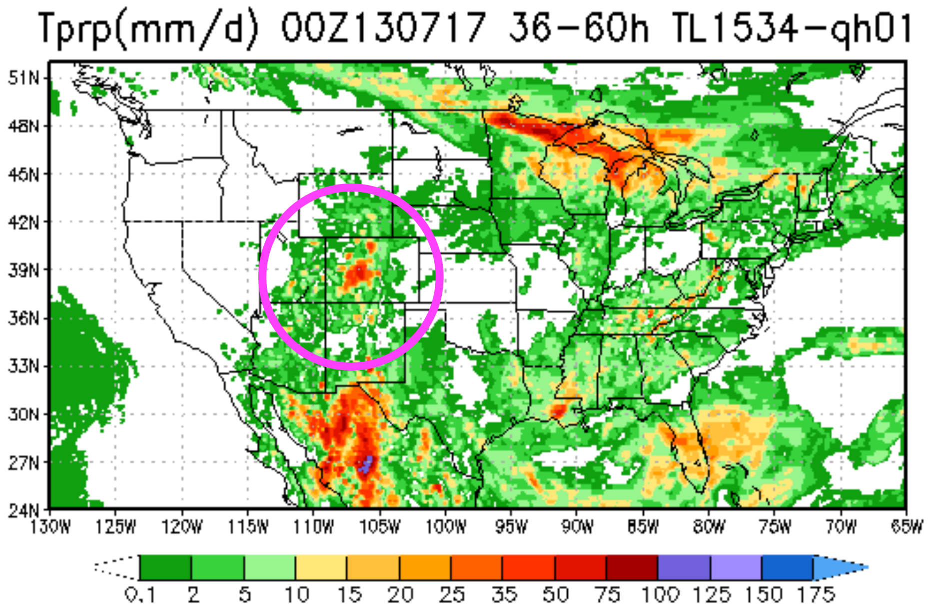
Reduction of the CRR (Convective Rain Ratio over the total rain amount) for higher resolution with the update

	CTL	Update
Total rain (mm/d)	3.28	3.32
Convective rain (mm/d)	2.17	1.82
CRR (Convective Rain Ratio[%])	66.2	54.8

Resolution: ~13 km

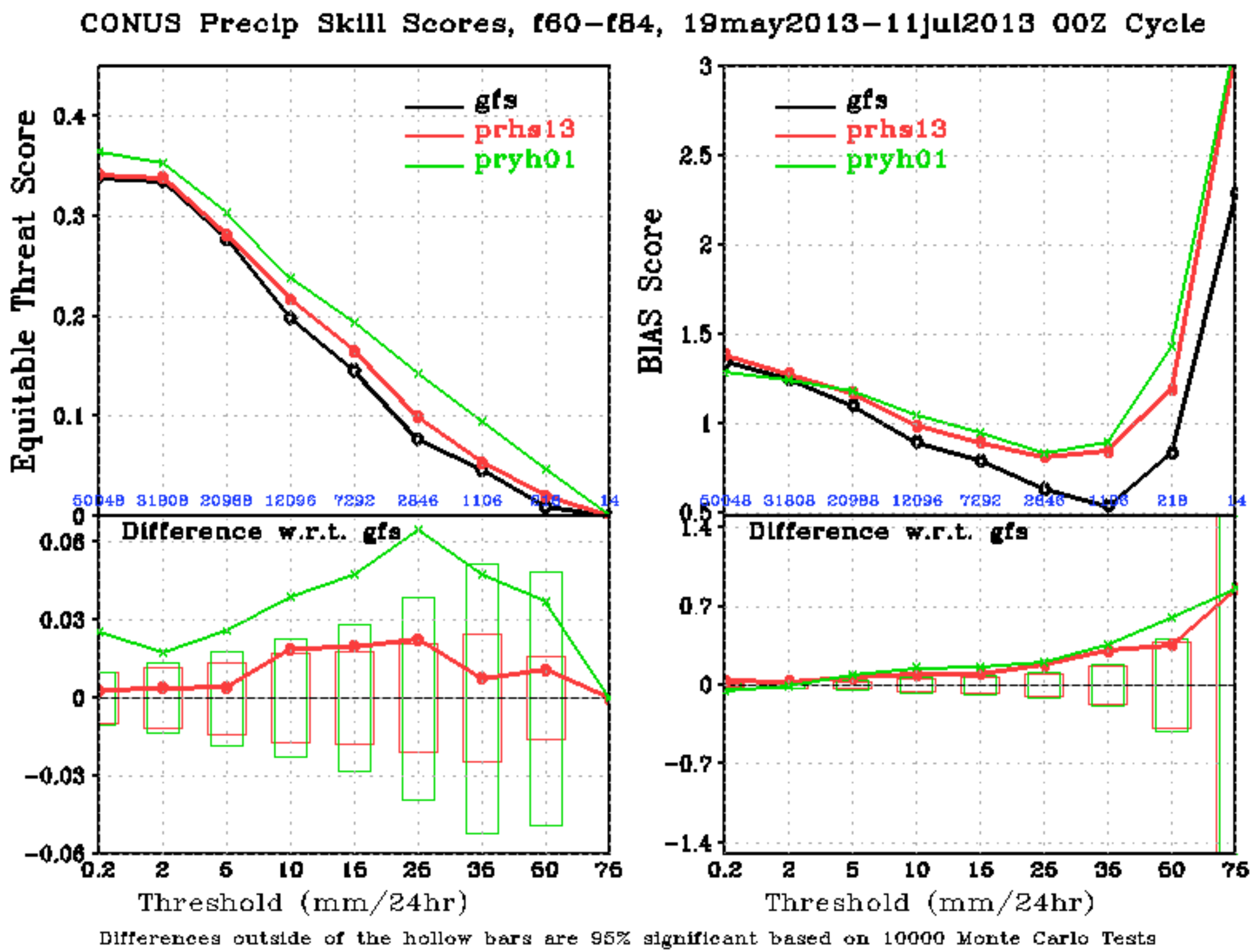


Control run

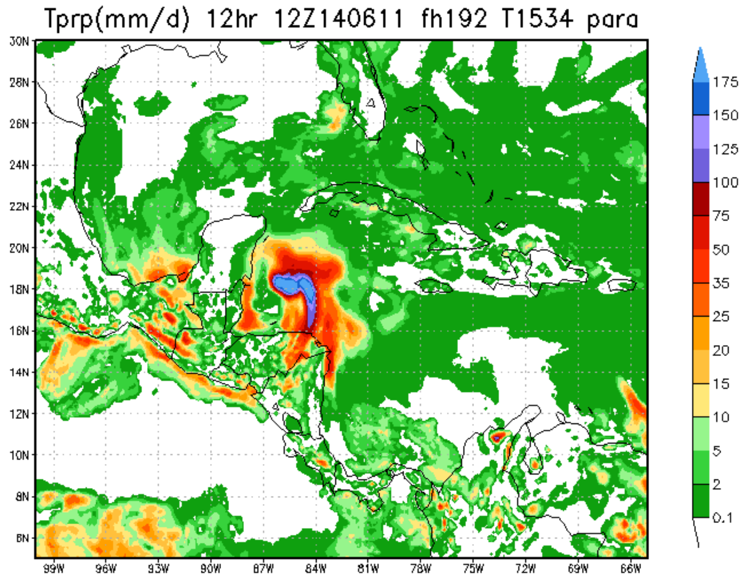


Experiment with modified trigger function (especially with CIN): reduce popcorn-like precip.

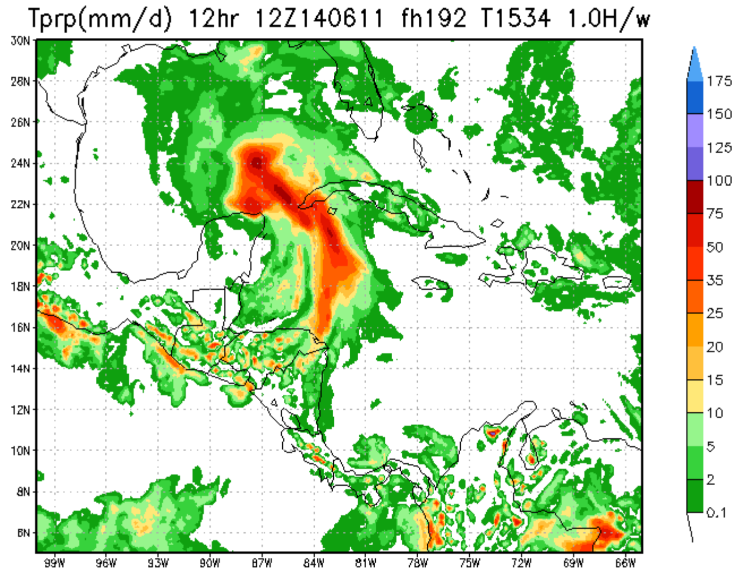
Equitable threat score and bias for precipitation forecasts during May 19 – July 11, 2013 (54 days)



Tests for false alarm tropical storms (8 day forecast)



CTL: Operational GFS (13km)



Updated convection schemes

False alarm tropical storms

- A scheme with stronger convection and easier trigger helps suppress false alarm storms, but it also suppresses an initial development of the real storm and makes it difficult for a forecaster to detect the real storm.
- On the other hand, a scheme with weaker convection and more strict trigger helps detect the early development of the real storm, but it tends to produce too many false alarm storms.
- The best scheme will be a scheme promoting real storms but suppressing spurious storms at the same time, which is very difficult to develop.
- Operational hurricane forecast center more concerns about the detection of the real storm rather than false alarm storms (Glenn White, EMC).

Future development

- Improve parameterizations of entrainment and detrainment rates as well as convection trigger function.
- Improve microphysical processes in cumulus convection schemes (e.g., rain/snow conversion, evaporation from convective rain/snow, etc.).
- Improve the deep convection scheme which promotes real storms but suppresses spurious storms at the same time.
- Develop a stochastic shallow convection scheme associated with the CPT project, where entrainment is assumed to occur as a discrete event with prescribed probability.
- Modify the scheme to have scale-aware capability.

Scale-aware parameterization

- Propose a simple parameterization, assuming that cloud base mass flux decreases with increasing the updraft area fraction, i.e.,

$$m_b' = (1-\sigma_u)m_b$$

σ_u: updraft area fraction (0~1.0)

m_b : original cloud base mass flux from AS quasi-equilibrium closure

m_b' : updated cloud base mass flux with a finite σ_u

σ_u??

1) Pan et al. (2014): $\sigma_u \approx \overline{w} / w_u$

$$\overline{w} = \sigma_u w_u + (1-\sigma_u)\tilde{w}_u$$

$$\frac{\partial w_u^2}{\partial z} = -b_1 \varepsilon w_u^2 + b_2 g \frac{T_v - \overline{T}_v}{\overline{T}_v}$$

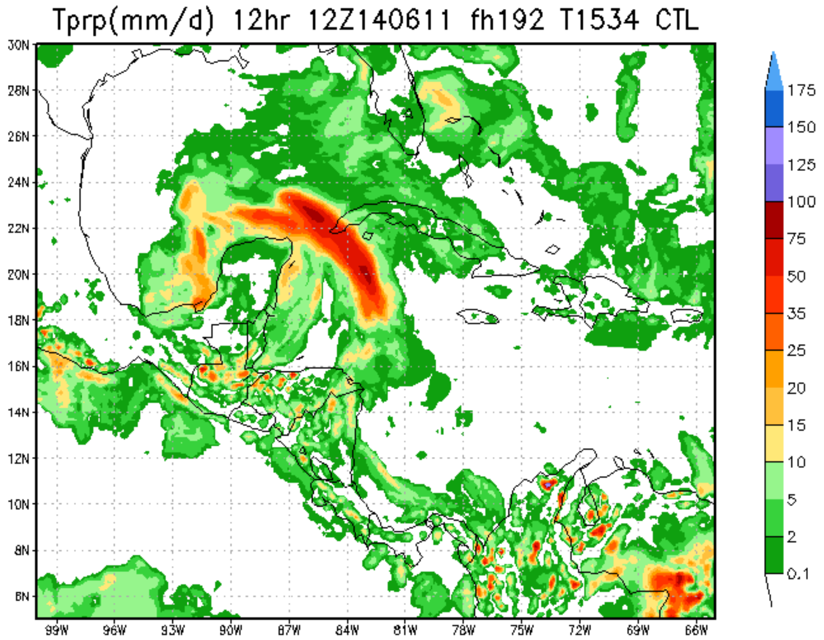
2) Arakawa & Wu (2013): $\sigma_u = \dfrac{(\overline{w'h'})_E}{\Delta w \Delta h + (\overline{w'h'})_E}$

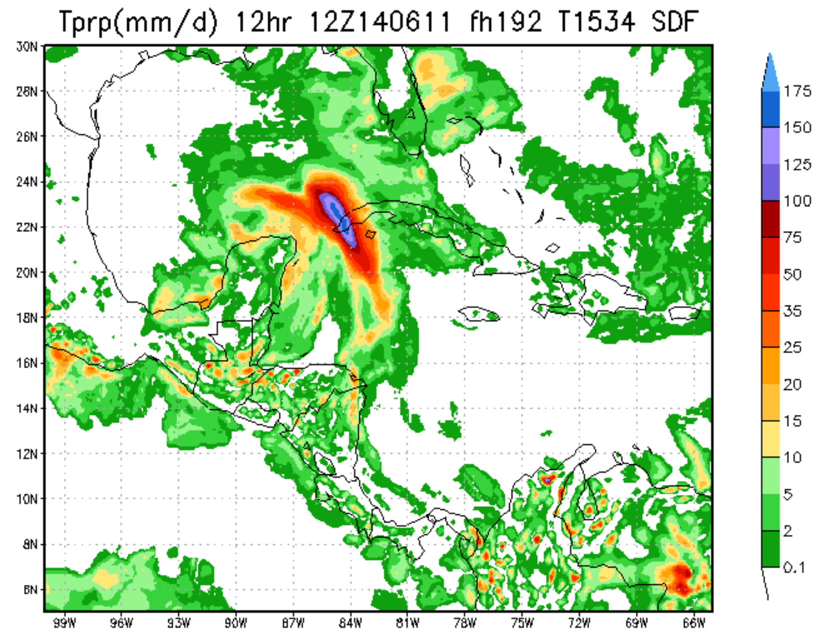
$(\overline{w'h'})_E$: equilibrium vertical eddy transport of moist static energy

Scale-aware parameterization (13 km)

CTL (13 km)

$$m_b' = (1 - \sigma_u) m_b \qquad \sigma_u \approx \overline{w} / w_u$$





False alarm storm case